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Energy Procedia 4 (2011) 2941–2949

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-10

PlantaCap: a Ligno-cellulose Bio-ethanol Plant with CCS

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Abstract

Deep reductions of greenhouse gas emissions in the automotive sector are difficult and often regarded as expensive. Use of ethanol from bio-resources is a potential way to reduce emissions. Ethanol produced from wheat typically reduces greenhouse gas emission by 35% (well-to-wheel) compared to gasoline. In principle, greenhouse gas emissions may be further reduced by applying carbon capture and storage to store the co-produced carbon dioxide. In this study we assessed the technical, economical, regulatory and greenhouse gas performance aspects of bio-ethanol production from ligno-cellulose for a hypothetical plant in Germany.
Reducing greenhouse gas emission by CCS from bio-ethanol plants is potentially economical attractive; for instance costs for a 170 kt sized bio-ethanol plant are estimated at 21 to 32 €/t of CO_2 stored. Emissions from ligno-cellulose based ethanol plants can be reduced by 150%, i.e. resulting in negative emission when using biomass and CCS combined. Potential revenues may come from ETS (requires adjustments), voluntary markets (probably not sufficient yet) and increased value of the ethanol (requires additional regulation). In some cases, it might be possible to sell high quality CO_2 on the market. At the moment, none of these is applicable except the food-grade sales or will yield sufficient income to cover the costs. However, some of them may provide opportunities in the future when rules or boundary conditions are changed.

Keywords: bioethanol, greenhouse gas performance, CCS, financing

doi:10.1016/j.egypro.2011.02.202

1. Introduction

CCS is often associated with the use of fossil fuels and primarily with the use of coal. However, CCS can also be combined with bio-energy production where short-cycle carbon is harvested and stored deep underground. This paper considers ethanol production from ligno-cellulose biomass through hydrolysis and fermentation combined with geological storage of CO_2. Bio-ethanol, produced through the fermentation of woody material waste, has an improved greenhouse gas balance compared to traditional automotive fuels, such as gasoline. Further emission reductions can be achieved by applying carbon capture and storage (CCS) to bio-ethanol plants. With capturing and storing the CO_2, CO_2 of the short carbon cycle is removed from the atmosphere during the process of producing and using bio-ethanol. Even negative CO_2 emissions might be achieved depending on the efficiency of the process.

This paper addresses the results of the techno-economic analysis of a hypothetical ligno-cellulose bio-ethanol plant with CCS in Germany. The project under study is a planned bio-ethanol plant combined with CCS in Germany. Bio-ethanol is produced through the fermentation of woody material waste. Ethanol production is about 170 kt ethanol per year. Corresponding CO_2 production is 0.17 – 0.20 Mt pure CO_2 per year. We analyze the greenhouse gas balance, the costs and investigate possible routes for creating financial incentives for such bio-ethanol plants with CCS in Germany.

2. Bio-ethanol plant with CCS

2.1. Bio-ethanol chain

There are several different routes to convert biomass to energy. This study considers ethanol production via hydrolyse and fermentation. This process produces relatively pure CO_2 as by-product of the fermentation process. Figure 1 gives a simplified generic configuration of ethanol production from ligno-cellulose biomass. Carbon dioxide results from the fermentation process where (C5 and C6) sugars are converted to ethanol and CO_2 and from the power generation process that delivers electricity for the distillation and dehydration steps. In this paper, only capture and storage of the CO_2 released from this fermentation process is included. The power generation process is outside the scope of this study.

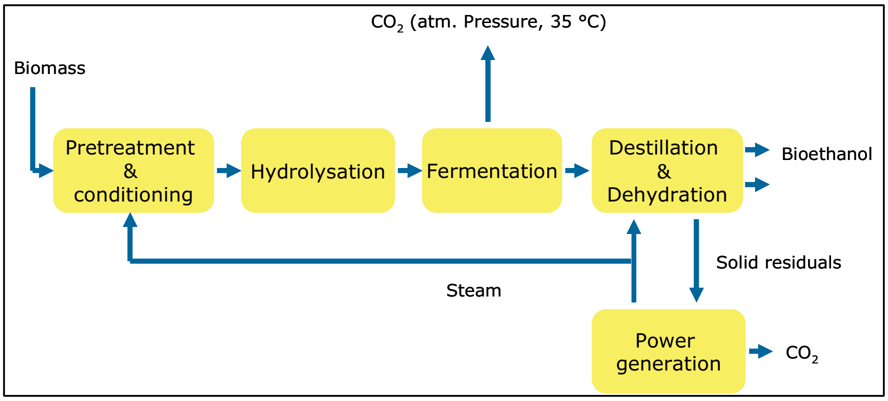

Figure 1 Schematic configuration of bio-ethanol chain with CCS

During the fermentation process, sugars (glucose) are converted to ethanol and carbon dioxide. Equation (1) shows the basic overall chemical reaction of the fermentation process.

$$C_6H_{12}O_6 \quad \rightarrow \quad 2\ C_2H_5OH + 2\ CO_2 \tag{1}$$

As can be seen from the reaction equation, for each mole of ethanol one mole of CO_2 is produced. The optimum temperature for the fermentation process is 35ºC, which is lower than the temperature of the hydrolysis step (60ºC) [1]. Normally, a cooling step is introduced between hydrolyse and fermentation. Also the operating pressures of the fermentation process are rather low. The concentration of CO_2 in the off gases of bio-ethanol plants typically is about 87% on a wet basis and about 98% on a dry basis [2]. The high purity of the CO_2 is an important aspect if application of carbon capture and storage is considered. Capture from high purity emission sources in general is much less expensive compared to CO_2 capture from power plants. The main impurities in this stream are: air (nitrogen and oxygen), water, alcohols (mainly ethanol), aldehydes, ketones and sulphur compounds (H_2S, dimethyl sulphide and carbonyl sulphide). The exact concentrations of these compounds mainly depend on the type of biomass feedstock and the process conditions.

The CO_2 stream is released at moderate temperatures and at atmospheric pressure. Higher pressures – which might be advantageous for the CO_2 capture process – have a negative impact on the fermentation process. The CO_2 stream leaves the fermenter at atmospheric pressure and at a temperature of 35 °C [1]. Other literature sources report slightly different temperatures for the CO_2 that leaves the fermenter: Toromont Systems (2004) [3] reports 49 °C and Trimeric Corporation (2006) [4] reports 27 °C.

2.2. CCS chain

2.2.1. Capture of CO_2

For transportation and injecting it is relevant that the CO_2 is at the right conditions, i.e the amount of other components in the CO_2 should be within acceptable limits. Based on a ‘typical’ composition of the CO_2 effluent from the fermentation process no critical concentrations have been identified. It is important that the CO_2 is sufficiently dry to transport and store it. The water content should be controlled, because of risks for hydrate formation and corrosion in pipelines and injection facilities. Oxygen concentration may be an issue when CO_2 stream is used in enhanced oil recovery. The oxygen may cause oil to burn which could affect the oil production and injection conditions negatively.

2.2.2. Compression and transportation of CO_2

The economically best mode of transport for the captured CO_2 is pipelines. A multi-stage centrifugal compressor is used to pressurize the CO_2. The optimal outlet pressure of the compressor depends on the transport distance, the volume of the CO_2 stream, and on the type of storage. Most likely, the stream transported most economically as a liquid at pressure of about 100 to 120 bars and less than 30 ºC. Under these conditions the density is about 800 to 900 kg/m^3 and two-phase flow can be avoided. The high density of the CO_2 implies that a relatively small diameter of 12 cm is sufficient to transport about 170,000 tonnes of CO_2 per year, the anticipated volume of the bioethanol plant. For larger distances, it might be more economical to increase the diameter. Alternatively, higher pressures may be used or a booster station be placed along the transmission line. The required compression energy is about 400 to 450 kJe per kg of CO_2. This implies required power capacity of about 2.5 MW_e. This amount of electricity can normally be covered by the co-production of a ligno-cellulose bio-ethanol plant.

2.2.3. Storage of CO_2

Applying CCS is only economical and meaningful if a storage site exists in the close vicinity of the bio-ethanol plant. Anticipating to the intended plant size and 20 years of operation, a minimum storage capacity of 5 Mt was required. Potential storage sites had to comply with the following geological conditions:

1) storage locations should have a minimum depth of 1000 meters below ground;
2) storage formations should have a gross thickness of more than 20 meters, and
3) storage formations should have a gross thickness of the barrier rock above the reservoir of at least 20 meter;
4) storage formations should be classified as aquifers according to a regional hydrogeologic classification.

Accordingly, the subsurface has been investigated within a radius of 75 km around Wolfsburg and Schwedt, the two possible candidate sites for the bio-ethanol plant in Germany.

Around Wolfsburg, in principle storage formations of Upper Rotliegend, Middle Bunter, Upper Keuper, Middle Jurassic, and Lower Cretaceous age comply with the requirements. Fourteen individual closed reservoir structures were selected for further characterization and calculation of storage capacities (see figure 2). These potential reservoirs are situated in depths between 1300 and about 4400 meters below ground. All structures are basically closed anticlines, mostly unfractured. The calculated CO_2 storage capacities range between 3.9 and 108 million tons (for 90 % simulated probability). Furthermore, within the screening area five gas fields are situated each having a CO_2 storage capacity of more than 5 million tonnes. However, four of these fields were still producing by the end of 2009.

Around Schwedt, in principle storage formations of Middle Bunter, Middle Keuper, and Upper Keuper/Lower Jurassic age comply with the requirements. Fifteen reservoir structures were selected for further characterization. These potential reservoirs (mostly unfractured anticlines) are situated in depths between 800 and 2300 meters below ground. In comparison to Wolfsburg, these reservoirs are situated in considerable shallower depth ranges. The calculated CO_2 storage capacities range between 5.3 and 190 million tonnes (for 90 % probability). Compared to Wolfsburg, deep wells (> 800 m) and 2D-seismic lines in the vicinity of the characterized structures are sparsely available. In summary, both candidate sites Wolfsburg and Schwedt meet the requirements for potential CO_2 storage.

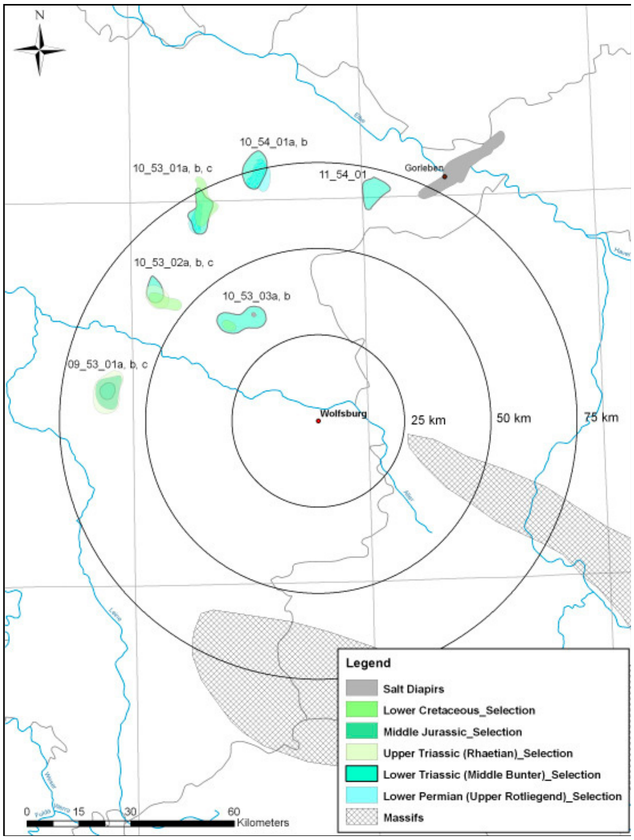

Figure 2. Location and areal extent of fourteen selected potential CO_2 storage structures in the surroundings of Wolfsburg

3. Greenhouse Gas Balance of ethanol supply chains

Greenhouse gas emission reduction is one of the drivers for biofuels policies. The well-to-wheel greenhouse gas performance of biofuels plays an important role in biofuels policies under development in various EU Member States. We expect that the greenhouse gas performance will play a role in the future economic value of a biofuel.

Well-to-wheel (WTW) greenhouse gas balances of the bioethanol chain with CCS have been calculated for five scenarios using the Greenhouse Gas Calculator for Biofuel[1]. These five scenarios include three ethanol-from-straw with CCS scenarios and two ethanol-from-wheat scenarios. These last ones are included for reason of comparison. The greenhouse gas (GHG) emissions are given relative to the fossil reference gasoline, which GHG emissions are normalized at 100% (see figure 3). All ethanol-from-straw with CCS concepts show net negative CO_2 emissions, which means that this concept removes CO_2 from the atmosphere. Relatively low emissions from agriculture combined with large avoided emissions in generating extra electricity and in capturing the CO_2 that results from the fermentation process contribute to these results.

In the ethanol-from-straw base case scenario (including CCS) the largest contribution to overall emissions is from the production of the feedstock (13%). More specifically, 11% of overall emissions are due to the production and application of nitrogen fertilizer and the associated N_2O emissions. The impact of using lingo-cellulose biomass combined with capturing and storing the CO_2 from the fermentation process is significant and reduces the GHG emissions of this specific ethanol-from-straw chain with over 100% compared to the gasoline scenario. During the combustion of one MJ of gasoline around 76 g of CO_2.is emitted. On the other hand, during the production of 1 MJ of bioethanol, 37 g of biogenic CO_2 is produced in the fermentation process. If all this CO_2 is captured and stored it could thus lead to an emission reduction of nearly 50% relative to the end-use emission of gasoline. Even if the capture efficiency of CO_2 is less than 100%, the total GHG emission reduction of the supply chain will still be significant.

The GHG emission performance of the ethanol-from-wheat scenarios is considerable less than the ethanol-from-straw scenarios. The ‘Default’ scenario assumes conservative values for several critical parameters, e.g. on fertilizer use and feedstock yield. Net emissions turn out to be significantly higher than its fossil reference gasoline due to unfavorable land use change and high emissions associated with the production and use of fertilizer. The ‘Typical’ scenario is based on more realistic and actual data. Figure 3 shows that for both scenarios the main contribution to overall GHG emissions is feedstock production and more specifically GHG emissions related to the production and use of fertilizer. GHG emissions of the ‘Typical’ scenario are 35% lower compared to the fossil reference gasoline.

[1] The Greenhouse Gas Calculator for Biofuels is a tool being developed by Ecofys for the Dutch government to assess the greenhouse gas performance of any biofuel supply chain via a uniform methodology. The tool is envisioned to be used by biofuel-obliged parties in the Netherlands to report on the greenhouse gas performance of the biofuels they deliver to the Dutch market.

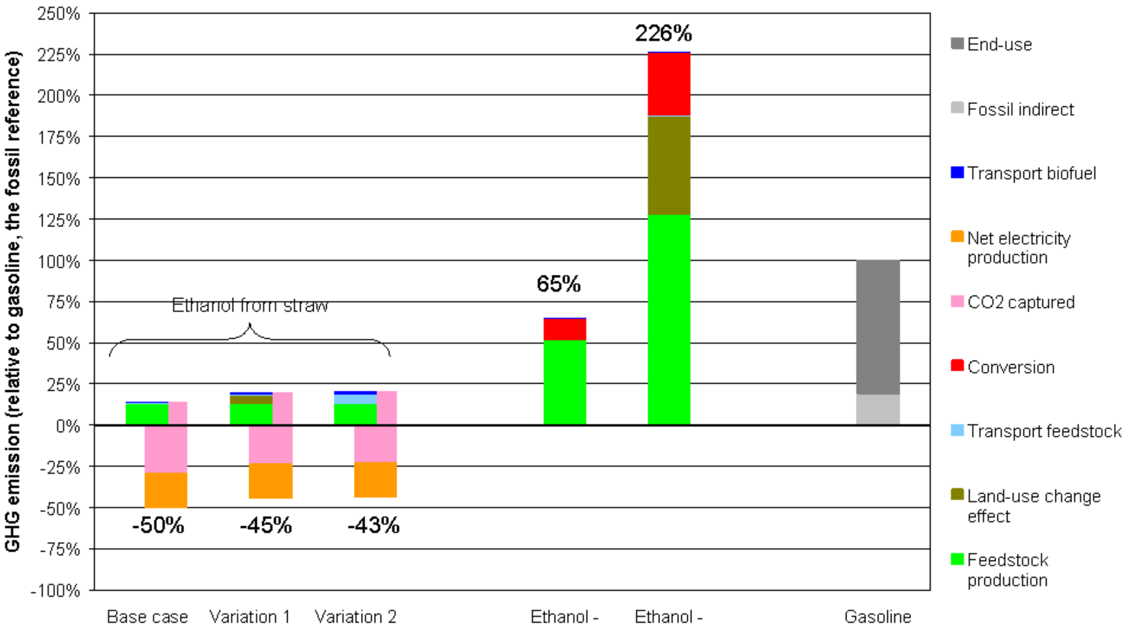

Figure 3 Greenhouse gas emissions of several ethanol supply chains relative to the gasoline reference

4. Costs of capture, transport and storage

4.1. Costs of CCS

The cost of the CCS chain is composed of investment costs and annual operational and maintenance costs. We distinguish the following cost elements for investment: capture (piping etc), compressor, transport, injection facility (storage site development including site selection, site characterization and seismic; abandonment of site) and project engineering and preparation (engineering, right-of-way, etc.). For annual costs we distinguish: maintenance costs of the equipment, cost of power, monitoring of storage location, communication and management. Costs have been calculated for low-cost and high-cost case, reflecting realistic and not extreme values. Total investment for CCS ranges from 21 to 32 M€. Using capital charge rate of 11%, total specific costs for CCS amount to 21 to 32 € per tonne of CO_2. Thirty percent of the total costs are related to pipeline costs. In this scenario we assumed a transport distance of 75 km. When no transport of the CO_2 is required cost could possibly reduce to 15 to 22 €/t. Figure 4 shows the low and high investment estimates (bars at the left hand) and annual costs (bars at right hand).

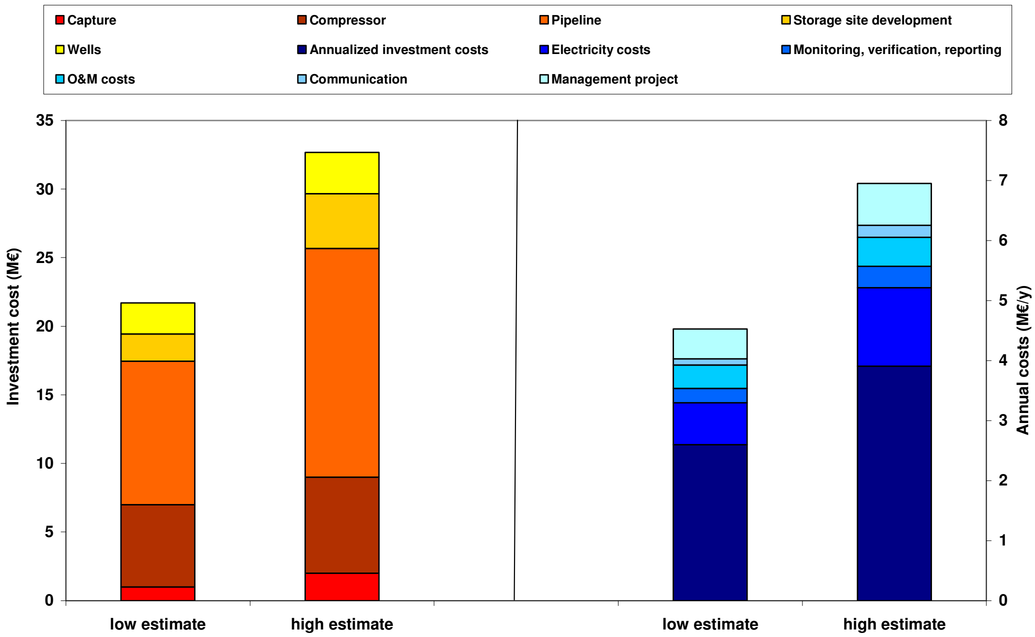

Figure 4 Estimate of investment costs and annual costs for capturing and storing 0.17 Mtonnes of CO_2 from a bioethanol plant

5. Financing mechanisms for bio-ethanol with CCS

Captured and stored CO_2 emissions from fermentation of wooden materials in the bio-ethanol plant might represent a value in future markets. Today it is not yet clear how CCS at bio-ethanol plants will be valued. First, CO_2 reduction by CCS from bio-ethanol plants may generate financial revenues by the increased value of bioethanol with a higher greenhouse gas performance. Policy developments on the accounting of biofuels and biofuel can influence the competiveness of bio-ethanol plants with CCS. The value of bio-ethanol might be increased by applying CCS when the GHG performance of the produced bio-ethanol is better compared to other biofuels.

Secondly, there are various ways to generate carbon credits by CCS at a bio-ethanol plant. Potential candidate markets explored in this paper are 1) the EU Emissions Trading Scheme (EU-ETS), 2) the voluntary carbon market and 3) flexible Kyoto Mechanism Joint Implementation/Domestic offsetting. In section 5.1 the generation of carbon credits is discussed in more detail.

Another option to be considered is to sell part of the captured CO_2 to the food industry in period of high demand instead of storing it underground. Prices may go up in such high demand periods to 40 to 80 €/t or higher. It should be noted that marketing, producing and distributing food grade CO_2 involves additional (investment) costs. The CO_2 needs to be cleaned, liquefied, stored and distributed. These activities will add to the costs. Selling CO_2 to the food industry will not yield carbon credits, thus the opportunity losses from unsold carbon credits have to be discounted from the CO_2 sales revenues.

5.1. Generation of carbon credits

Under the EU-ETS, listed installations are obliged to reduce their CO_2 emissions below an appointed cap. The EU-ETS operates by the allocation and trading of greenhouse gas emissions allowances (EUAs) throughout the EU.

From the start of Phase II of the EU ETS in 2008, Member States could decide to 'opt-in' CCS projects under the EU ETS, subject to Commission approval. More recent developments led to see CCS officially recognized within the 2009 revised EU ETS, which will take effect from Phase III in 2013. The inclusion of CCS activities within the revised EU ETS means that emissions allowances need not be surrendered where CO_2 is successfully captured and stored. These emissions will therefore count as 'not emitted'. On the other hand, bio-energy conversion installations are not included in the EU-ETS system and will not be included in the next phase of the EU-ETS (2013 – 2020) either. Storing CO_2 from biomass will not 'create' sellable allowances under the EU ETS, i.e. there is no economic value attached to 'negative emissions'. Consequently, there is no incentive for the bio-ethanol chain with CCS under the current EU ETS.

Besides the regulatory EU-ETS and Kyoto Mechanisms the possibility exists to trade carbon credits on voluntary carbon markets. The voluntary market generally applies to companies, individuals, and other entities and activities not subject to mandatory limitations that wish to offset GHG emissions. The voluntary market has been very small compared to the regulatory market, but has been growing quickly in recent years. Currently, a significant number of voluntary carbon market standards exist: Voluntary Carbon Standard (VCS), Voluntary Gold Standard, VER+ (Tüv-sud), Climate, Community & Biodiversity (CCB) Standard, Chicago Climate Exchange (CCX), ISO 14064, Climate neutral network and Green-e. Based on the information provided on these standards it is concluded that only Voluntary Carbon Standard (VCS) and the VER+ can be applied for CCS at bio-ethanol plants. Other voluntary markets do not apply because they explicitly focus on renewable energy and energy efficiency or require approved JI/CDM methodologies. It should be noted that it is important to choose a carbon standard that is recognized by customers and other stakeholders. Also it should provide a guarantee for the buyer that the carbon credits result in permanent equivalent offsets. The observed range of carbon prices on the voluntary market is significant. From the wholesale to the retail level, offsets range from less than 5.00 euro to around 30.00 euro per tonne of CO_2 equivalent [5].

As a third option, carbon credits might be generated under the JI scheme. Through the "linking directive", companies in EU Annex I countries will be able to buy Emission Reduction Units (ERUs) from JI projects in other JI countries to help them meeting their targets or to sell credits to other parties. The domestic market for generation of ERUs from JI projects is only sufficiently regulated in France (NB: 2008 situation). In other Annex I countries further regulation is required. Under the JI scheme, just like with the EU-ETS, CO_2 emissions from biomass are not accounted for under the current UNFCCC accounting rules. Germany would not be willingly to approve the creation of ERUs, because it would lower their national allowances to cover for their actual emissions. Another issue relates to the unavailability of methodologies under the CDM/JI mechanisms. At present time (NB: 2008 situation), the way in which CCS projects could be included in the CDM and JI is still under review.

6. Conclusions

We discussed various routes for revenues when applying CCS to a bio-ethanol plant. The revenues should be seen in the view of the costs of 21 to 32 €/t of CO_2 stored or possibly 15 to 22 €/t when no transport is required. Emissions from ligno-cellulose based ethanol plants can be reduced by 150%, i.e. resulting in negative emission when using biomass and CCS combined. Five possible revenues streams have been identified: higher valuation of the bio-ethanol, CO_2 food grade sales for industry, EU-ETS, JI/CDM and domestic offset and voluntary markets. At the moment, none of these is applicable (except the food-grade sales) or will yield sufficient income to cover the costs. Nevertheless, some of them may provide opportunities in the future when rules or boundary conditions are changed.

The ETS market is in principal very interesting as prices are predicted between the 20 and 50 €/t. However, currently CCS is not recognized under the ETS and emissions from biogenic origin (except land use change) are not accounted for in the UNFCCC national inventory and the Kyoto Protocol. Both issues have to be resolved before projects like PlantaCap can obtain EUAs for its emissions.

The most interesting option is to generate revenues by increasing the value of the produced bio-ethanol. A relative small increase of 5% of the price of bio-ethanol may be (more than) sufficient to cover the total costs of CCS. In Germany, regulation on emission reduction thresholds for biofuels is being prepared. Whether it will be possible to increase revenues by selling biofuels with a better greenhouse gas performance is still uncertain. One of the opportunities might be the blending with biofuels with lower greenhouse gas emission performance.

It should be noted that only one revenue stream at a time can be tapped. Inclusion in the ETS will not allow for selling anymore on the voluntary market. Also if the route of valorization through the greenhouse gas performance is chosen, no emission allowance units can be obtained anymore. It might be possible to split the emission reduction by selling part of the CO_2 emission reduction on the ETS market (when applicable) and attribute partly of the emission reduction to the biofuels to obtain the threshold (when in place).

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